EEU44C04 / CS4031 / CS7NS3 / EEP55C27
Next Generation Networks

Mobile architectures: LTE, LTE-A, LTE-A-PRO

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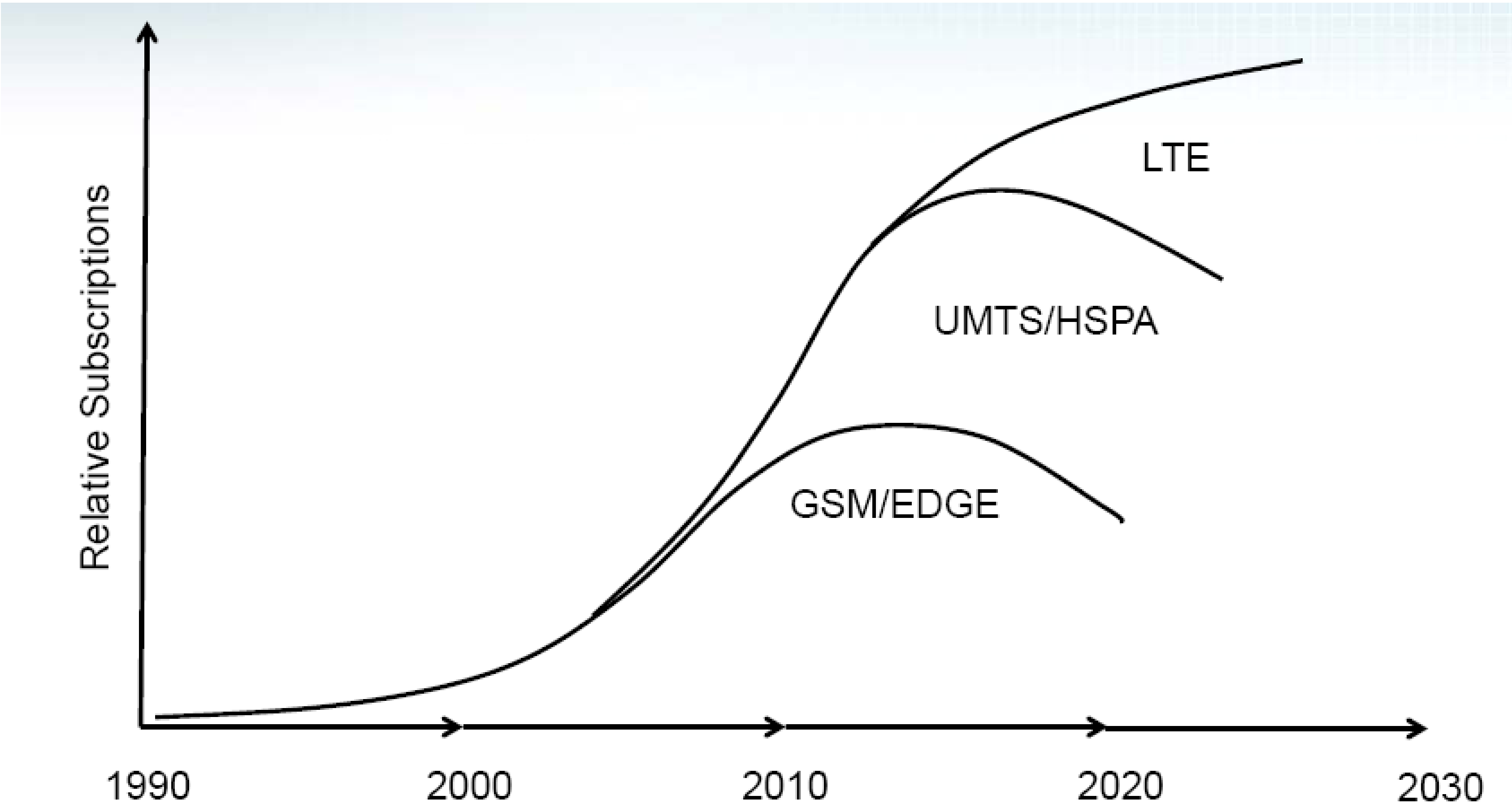
Motivation

- Evolution from 2G and 3G cellular systems
- Drivers
  - ✓ Exponential increase in demand
  - ✓ Support for higher data rates
  - ✓ Need for lower latency
  - ✓ Inter-networking with legacy network
  - ✓ Flexibility in spectrum use
  - ✓ Lower capital and operating expenses for network operator
- Smooth transition to 4G (IMT-Advanced)

LTE = Long Term Evolution

Projected adoption



Source: P. Rysavy, “Transition to 4G”, 2010

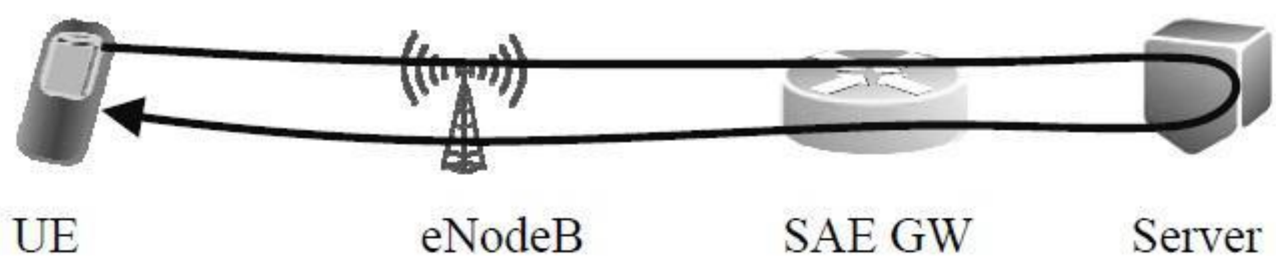
LTE performance objectives

- 100 Mbps peak DL, 50 Mbps peak UL
  - ✓ An order of magnitude higher for LTE+
  - ✓ Reduced latency (down to 10 ms)
  - ✓ Scalable bandwidth (up to 20 MHz)
- Backward compatibility with GSM/EDGE/UMTS
  - ✓ Handover and roaming to legacy networks
  - ✓ Use of existing spectrum
- Wide application
  - ✓ FDD (paired) and TDD (unpaired) operation
  - ✓ Mobility up to 350 km/h
  - ✓ Wide range of terminals: phones, smartphones, cameras, …

DL = Down-Link
UL = Up-Link
TDD/FDD = Time/Frequency Division Duplexing

What is latency?

- The time that passes from a user sending a piece of data request (e.g., file download or loading a webpage), to the time when the user gets a response
  - ✓ Sometimes more important than the bit rate offered
- The latency can be measured by the time it takes for an IP packet to travel from the terminal through the network to the Internet server, and back



Round trip time measurement

"Latency in LTE Systems", available online

SAE = System Architecture Evolution

LTE Features

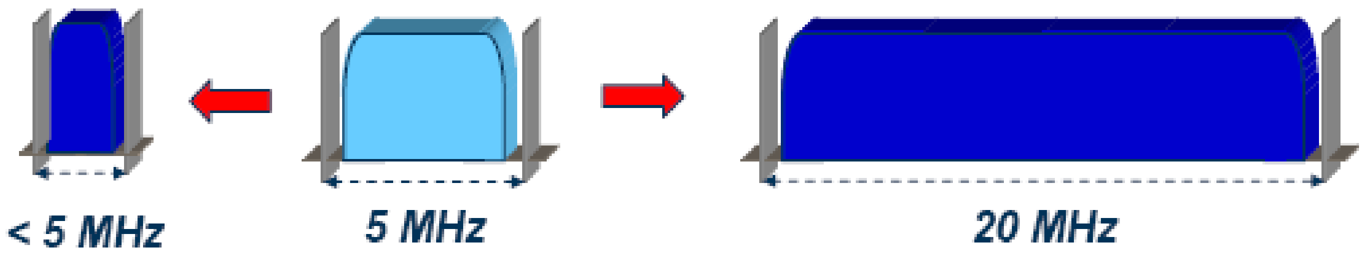
- OFDM/OFDMA
  - ✓ Increased spectral efficiency → increased data rates
- All-IP architecture
  - ✓ Simplified network management
  - ✓ Reduced CAPEX and OPEX
- Spectrum flexibility
  - ✓ Operation in various bands, with variable bandwidth
  - ✓ Resource aggregation

OFDM = Orthogonal Frequency Division Multiplexing
OFDMA = Orthogonal Frequency Division Multiple Access

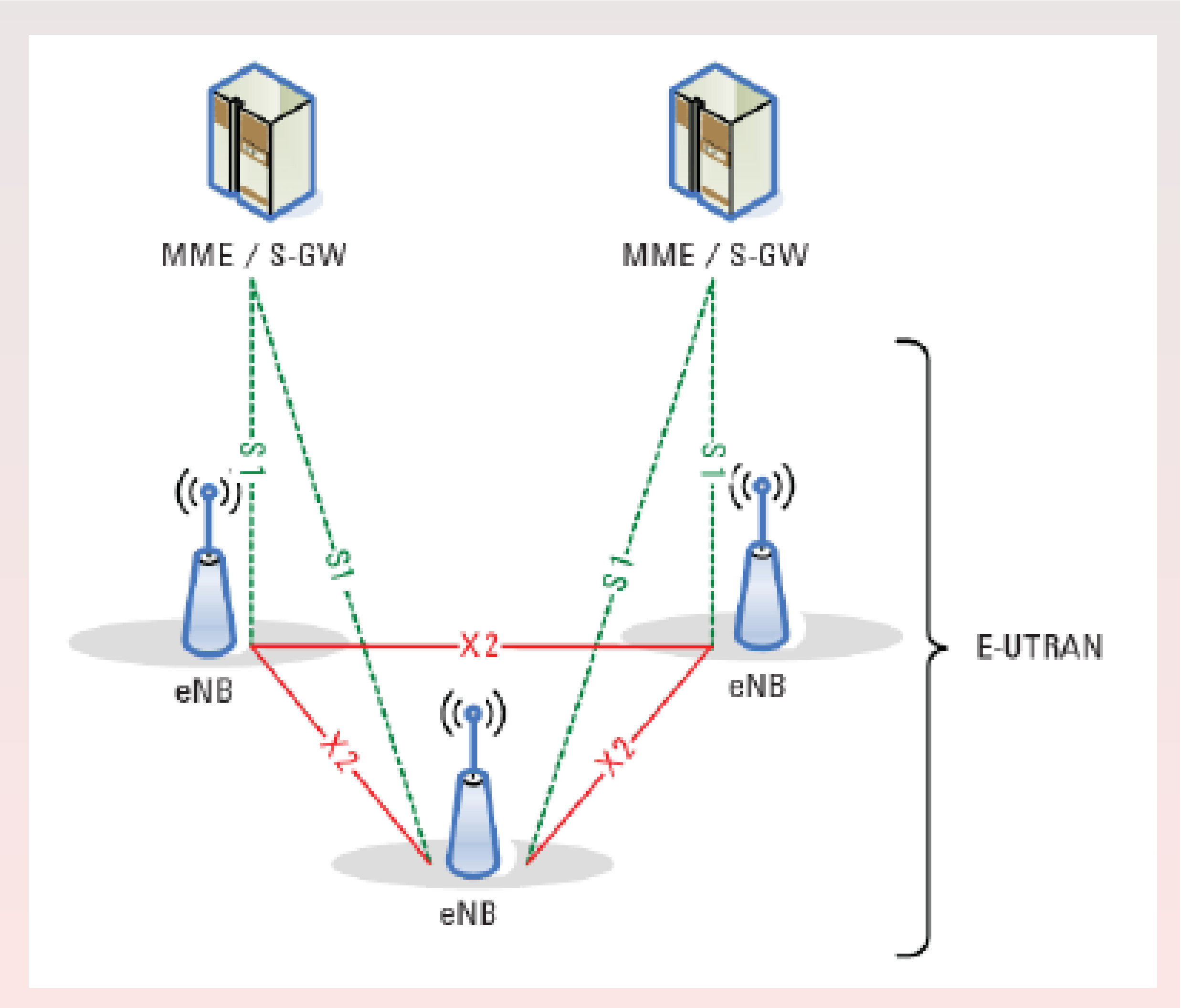
Spectrum flexibility

- Operation in a wide range of spectrum
  - ✓ Current and future 3G spectrum
  - ✓ Migration of 2G spectrum (e.g., 900 MHz)
  - ✓ Refarming of spectrum (e.g., UHF, 300 MHz–3 GHz)

- Operation in different-sized bands
  - ✓ Up to 20 MHz to support high data rates
  - ✓ Less than 5 MHz to enable smooth spectrum migration



Architecture



MME = Mobility Management Entity

S-GW = Serving Gateway

eNB = Evolved Node B

E-UTRAN = Evolved Universal Terrestrial Radio Access Network

Protocol layers

- Packet data convergence protocol (PDCP) → Layer 2
  - ✓ IP header compression
  - ✓ Cyphering and integrity protection
- Radio link control (RLC) → L2
  - ✓ Segmentation and concatenation
  - ✓ Retransmission handling
  - ✓ In-order delivery to higher layers
- Medium access control (MAC) → L2
  - ✓ Uplink and downlink scheduling at eNB
  - ✓ Hybrid Automatic Repeat ReQuest (HARQ)
- Physical layer (PHY) → L1
  - ✓ Coding/decoding
  - ✓ Modulation/demodulation (OFDM)
  - ✓ Multi-antenna use

CRC = Cyclic Redundancy Check

PHY

- OFDMA with cyclic prefix in DL, SC-FDMA with cyclic prefix in UL
- Duplexing: FDD and TDD
- 10 ms radio frames, containing 20 slots of 0.5 ms duration
- Supported modulation schemes: QPSK, 16-QAM, 64-QAM
  - ✓ Broadcast channel uses QPSK
- Maximum information block size: 6144 bits
- CRC-24 for error detection

Question: why does the broadcast channel use QPSK?

Scheduling

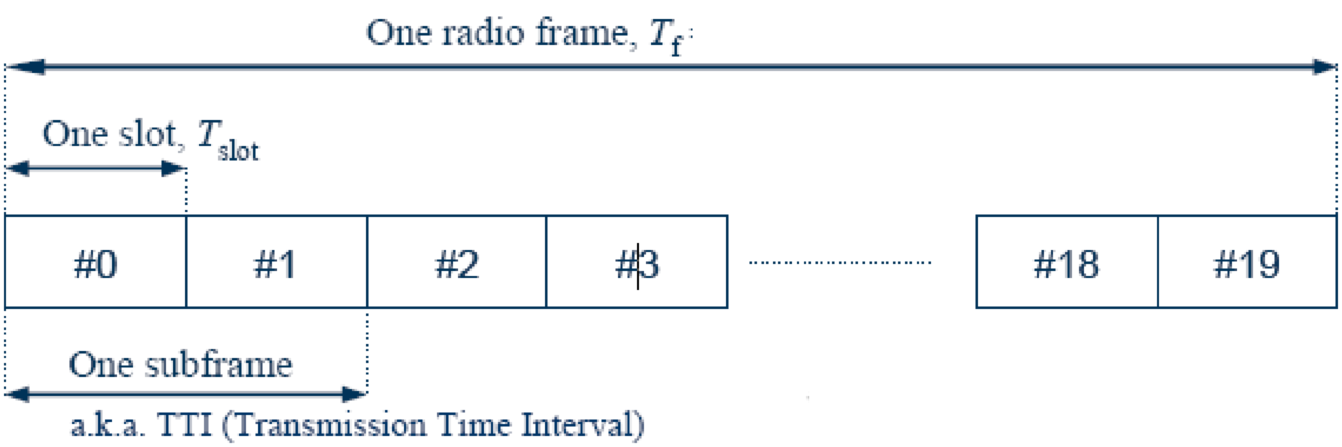
- Scheduler in eNB allocates resource blocks (which are the smallest elements of resource allocation) to users for predetermined amount of time
- Slots consist of either 6 (for long cyclic prefix) or 7 (for short cyclic prefix) OFDM symbols
- Longer cyclic prefixes are used to address longer multipath fading channel length
- Number of available subcarriers changes depending on transmission bandwidth
  - ✓ Subcarrier spacing is fixed

OFDMA (1)

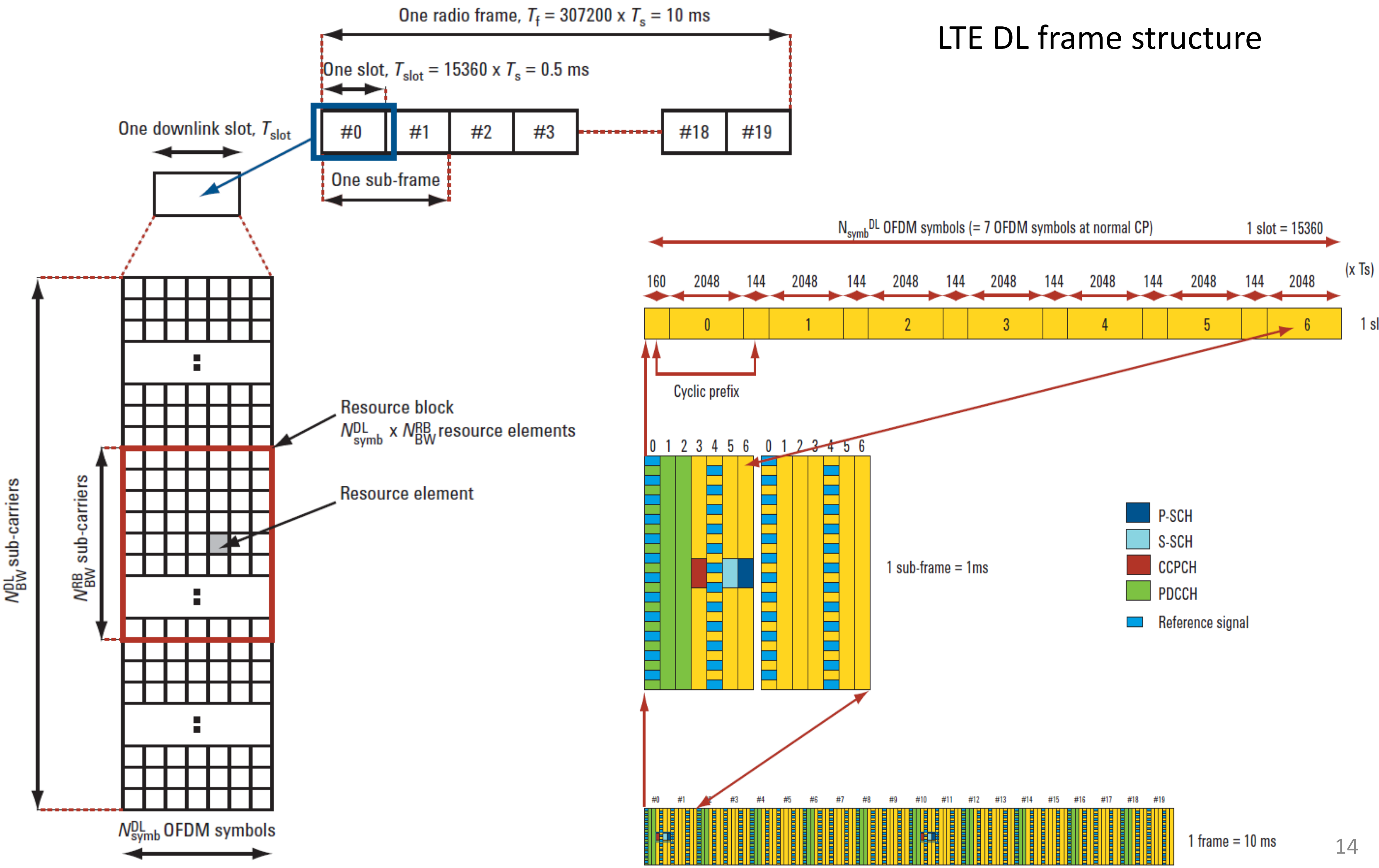
- OFDM uses a large number of narrow sub-carriers for multi-carrier transmission
- The basic LTE downlink physical resource can be seen as a *time-frequency grid*
  - ✓ In the frequency domain, the spacing between the subcarriers is $\Delta f = 15kHz$
  - ✓ Symbol duration time: $1/\Delta f$ + cyclic prefix
  - ✓ Cyclic prefix is used to avoid inter-symbol interference and allows the use of simpler receiver architectures (one-tap equalizer)
- One resource element carries QPSK, 16QAM or 64QAM
  - ✓ e.g., 64QAM: 6 bits per resource element

OFDMA (2)

- OFDM symbols are grouped into resource blocks
  - ✓ Resource blocks have a total size of 180kHz in the frequency domain and 0.5ms in the time domain
  - ✓ Each 1ms Transmission Time Interval (TTI) consists of two slots (T_{slot})



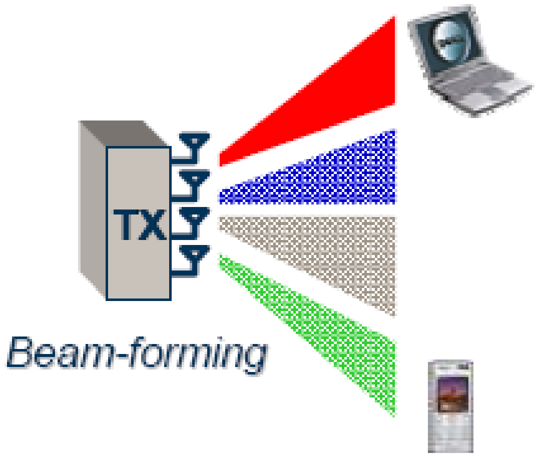
OFDMA (3)

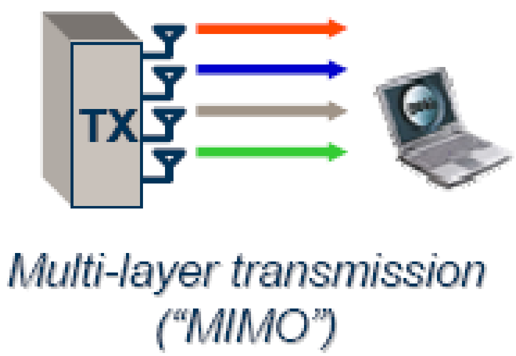


LTE DL frame structure

Multi-Antenna techniques

- Transmit Diversity
- Beam-forming
- Spatial multiplexing (a.k.a. multi-layer transmission)
- Multi-user MIMO





MIMO = Multiple Input Multiple Output

Services

Service category	LTE environment
Rich voice	VoIP, high quality video conferencing
P2F messaging	Photo messages, IM, mobile e-mail, video messaging
Browsing	Super-fast browsing, uploading content to social networking sites
Paid information	E-newspapers, high quality audio streaming
Personalisation	Realtones (original artist recordings), personalised mobile web sites
Games	A consistent online gaming experience across both fixed and mobile networks
TV/ video on demand	Broadcast television services, true on-demand television, high quality video streaming
Music	High quality music downloading and storage
Content messaging and cross media	Wide scale distribution of video clips, karaoke services, video-based mobile advertising
M-commerce	Mobile handsets as payment devices, with payment details carried over high speed networks to enable rapid completion of transactions
Mobile data networking	P2P file transfer, business applications, application sharing, M2M communication, mobile intranet/ extranet

LTE Advanced (LTE+): goals

- *Peak data rates*: DL - 1 Gbps; UL - 500 Mbps
- *Spectrum efficiency*: 3 times greater than LTE
- *Peak spectrum efficiency*: DL - 30 bps/Hz; UL - 15 bps/Hz
- *Spectrum use*: the ability to support scalable bandwidth use and spectrum aggregation (non-contiguous spectrum use)
- *Latency*: from Idle to Connected in < 50 ms; < 5 ms one way for individual packet transmission
- *More advanced MIMO*
- *Cell edge user throughput*: twice that of LTE
- *Average user throughput* : 3 times that of LTE
- *Mobility*: same as that in LTE
- *Compatibility*: LTE Advanced shall be capable of interworking with LTE and 3GPP legacy systems

4G/LTE-A subscriptions worldwide: in 2016

LTE Advanced is being rapidly deployed globally

Evolving for faster, better mobile broadband

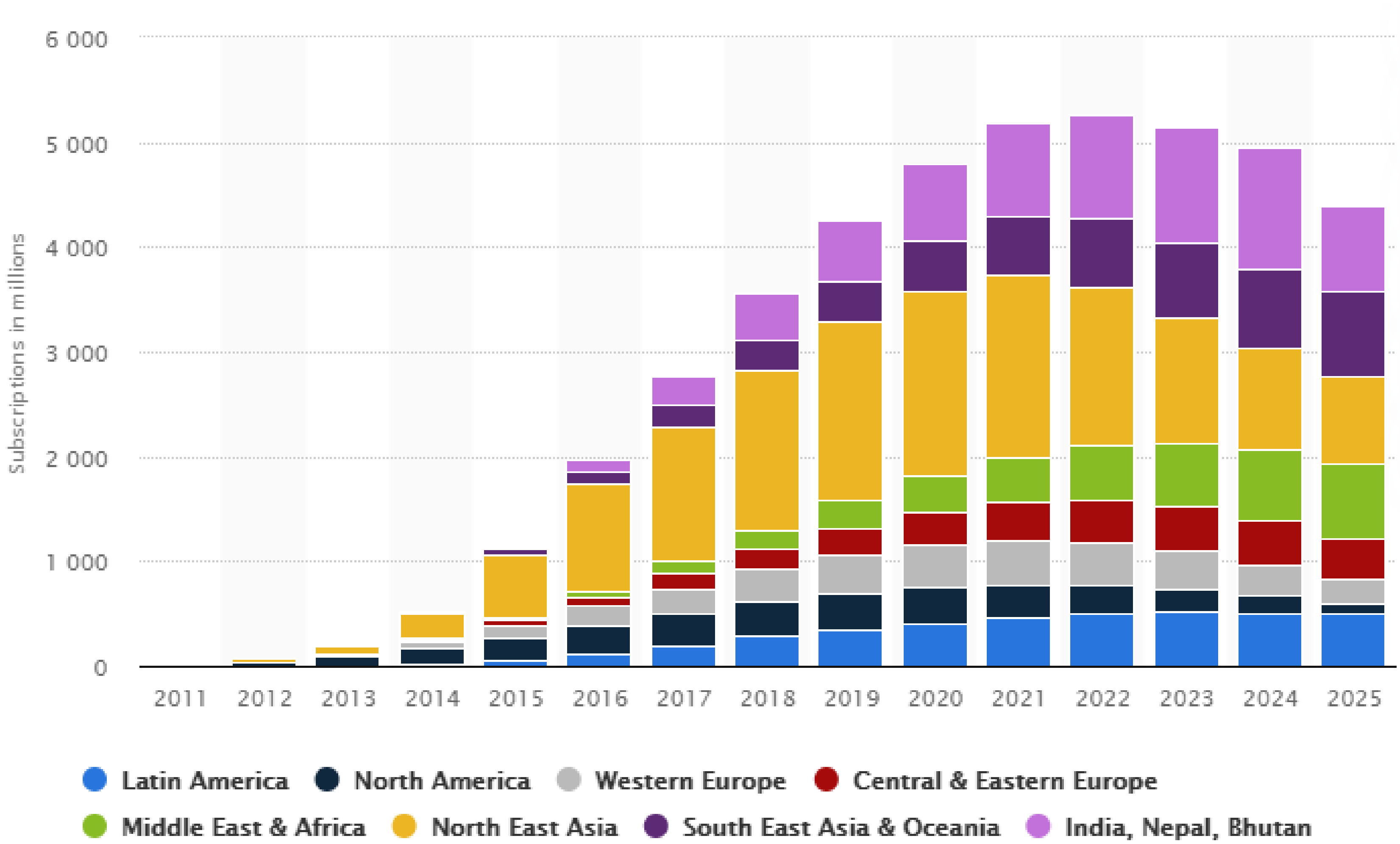
95+ | Commercial network launches in 48 countries

1,500+ | Commercial devices across 100s of vendors

>900M | LTE / LTE Advanced subscriptions worldwide

Qualcomm, "Leading the path towards 5G with LTE Advanced Pro", Jan 2016

4G subscriptions worldwide: NOW

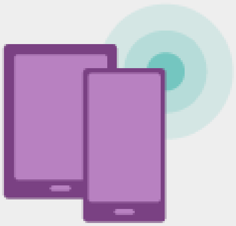


https://www.statista.com/statistics/521572/4g-5g-mobile-subscriptions-worldwide/

Introducing LTE Advanced Pro

Rising up to meet the significant expanding connectivity needs of tomorrow

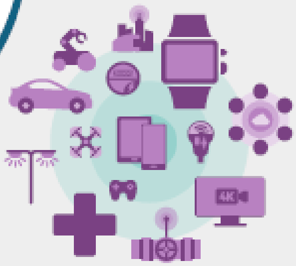
3GPP Release 13+



Propel mobile broadband even further

Enhance the mobile broadband experience and continue to deliver solutions to efficiently grow capacity

Progress LTE capabilities towards a unified, more capable 5G platform



Proliferate LTE to new use cases

Connecting new industries, enabling new services and empowering new user experiences

Qualcomm, "Leading the path towards 5G with LTE Advanced Pro", Jan 2016

Propel mobile broadband even further

Enhance user experience and deliver efficient solutions to increase capacity

Gbps+ peak rates

More uniform experience

Better coverage

Significantly lower latencies

Carrier Aggregation evolution—wider bandwidths

Aggregating more carriers, diverse spectrum types and across different cells

LTE in unlicensed spectrum

Make the best use of the vast amounts of unlicensed spectrum available

TDD/FDD evolution—faster, more flexible

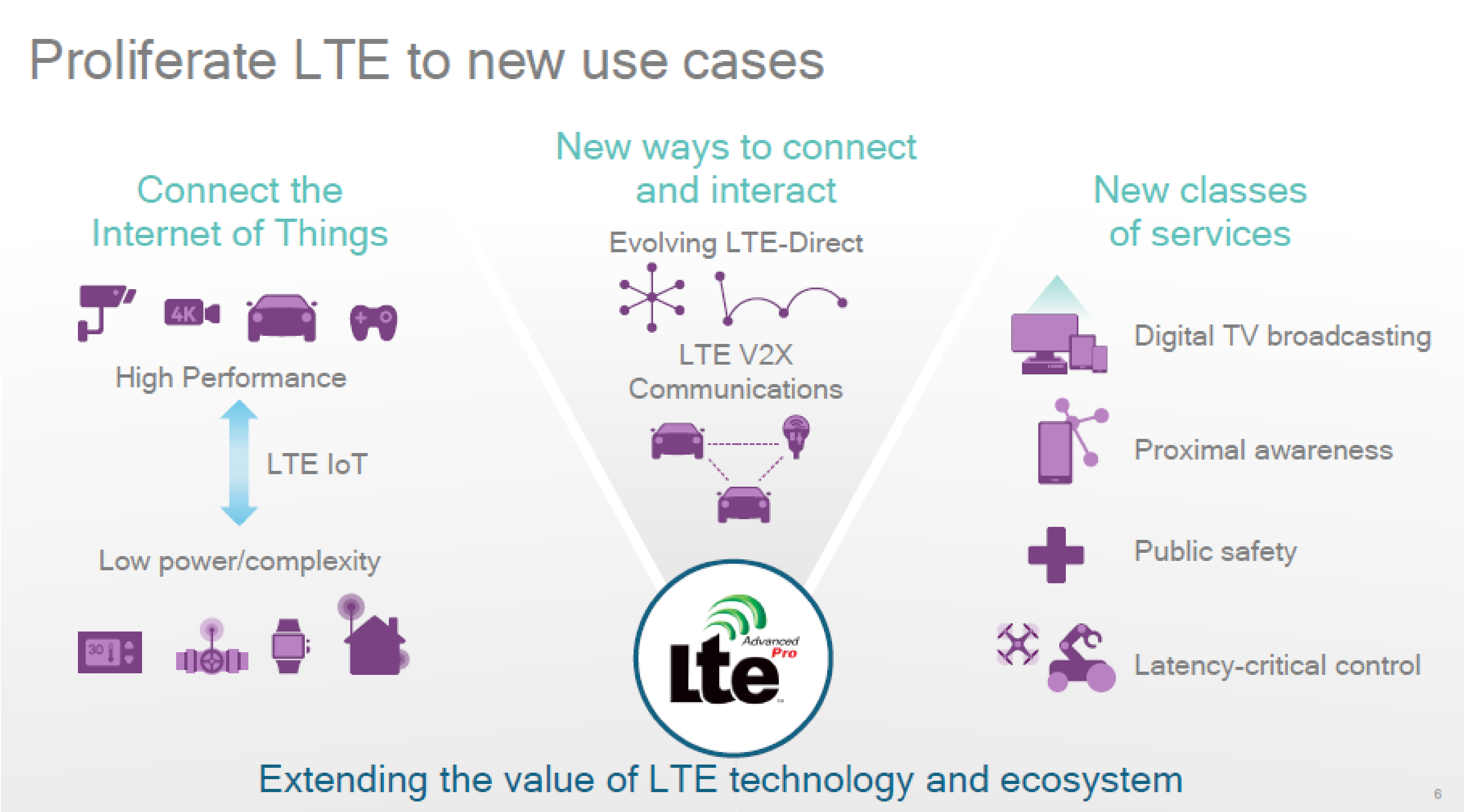
Enable significantly lower latency, adaptive UL/DL configuration, and more

Many more antennas—path to massive MIMO

Exploit 3D beamforming (FD-MIMO) to increase capacity and coverage

FD-MIMO = Full Dimension Multiple Input Multiple Output

Qualcomm, "Leading the path towards 5G with LTE Advanced Pro", Jan 2016



V2X = Vehicle-to-everything

Qualcomm, "Leading the path towards 5G with LTE Advanced Pro", Jan 2016

For which of the following devices the battery lifetime is **<u>not</u>** a metric of major interest?

- ❑ Wireless sensors
- ❑ Mobile phones
- ❑ Cellular base stations

For which of the following devices the battery lifetime is NOT a metric of major interest?

- ❑ Wireless sensors
- ❑ Mobile phones
- ✓ Cellular base stations

Cellular base stations are generally cabled, so the power replenishment is not a major issue, as compared to wireless sensors and mobile phones

Which of these access techniques is the one adopted in 4^{th} generation cellular systems (LTE/LTE-A)?

- ❑ TDMA
- ❑ OFDMA
- ❑ CDMA

Which of these access techniques is the one adopted in 4th generation cellular systems (LTE/LTE-A)?

- ❑ TDMA
- ✓ OFDMA
- ❑ CDMA

OFDMA is the correct answer. TDMA is used in 2G, and CDMA in 3G.

A scheduler is a system component in charge of allocating over time the radio resources needed to transmit to the wireless users.

- A Round Robin (RR) schedules users in a round-robin fashion, i.e., cyclically. Another feature of RR, is that it also schedules users independently of their channel conditions.

- A Maximum Carrier/Interference (Max C/I) schedules at time t the user n_{max} such that

$$n_{\max} = \arg\max_{n} \{d_n(t)\}$$

Where $d_n(t)$ is the expected throughput of user n at time t, if scheduled.

- A Proportional Fair (PF) schedules at time t the user n_{max} such that

$$n_{\max} = \arg\max_{n} \{d_n(t) / r_n(t)\} \qquad \textbf{(1)}$$

Where $d_n(t)$ is the expected throughput of user n at time t, if scheduled, and $r_n(t)$ the average past throughput, i.e.,

$$r_n(t) = \overline{d_n(t')} \ , \quad t' < t$$

a) Which of the three above schedulers maximizes fairness in resources allocation? Which maximizes throughput? Which achieves a trade-off between fairness and throughput?

b) Suppose we are given the following throughput traces for three users U_1, U_2, U_3 at times $t-2$, $t-1$, and the expected throughput at time t.

	$d_n(t-2)$ [Mbps]	$d_n(t-1)$ [Mbps]	$d_n(t)$ [Mbps]
U_1	0.5	1	0.8
U_2	2	1.7	1.5
U_3	0.6	1.1	2.1

Which users are going to be scheduled by RR, PF and Max C/I at time t?

a) - RR maximizes fairness.

- Max C/I maximizes throughput.
- PF achieves a trade-off, as its scheduling metric (see eq. (1)) takes into account both the throughput, and what happened in the past, equalizing the allocation of resources
  - ✓ if high allocation (and therefore high throughput) in the past, scheduling metric decreases
  - ✓ if low allocation in the past, scheduling metric increases

b) - RR allocates blindly and cyclically. Therefore if at $(t-2, t-1)$ allocation was, e.g., (U_1, U_2) at t RR will schedule U_3. Any other scheduled users' triple is equally valid.

- Max C/I will allocate U_3 at t, since $d_3(t)=2.1 > d_2(t)=1.5 > d_1(t)=0.8$

- PF will also allocate U_3, since

$$
\begin{aligned}
& d_3(t)/r_3(t) = 2.1/\left[(0.6+1.1)/2\right] \approx 2.47 \\
& > d_1(t)/r_1(t) = 0.8/\left[(0.5+1)/2\right] \approx 1.07 \\
& > d_2(t)/r_2(t) = 1.5/\left[(2+1.7)/2\right] \approx 0.81
\end{aligned}
$$